

# Search for the Higgs Boson Produced in Association with Top Quarks Using $9.4\text{ }fb^{-1}$

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## Abstract

We present a new Higgs search analysis using the  $t\bar{t}H$  associated production channel in the lepton plus jets final state. This analysis has a similar final state to the existing  $WH \rightarrow \ell\nu b\bar{b}$  analysis, so we have used much of the existing  $WH$  machinery. We exploit the high jet and high  $b$ -jet multiplicity in these events to both select a sample expected to contain  $t\bar{t}H$  and to maintain orthogonality with other Higgs searches using the lepton plus jets final state. We search for a Higgs boson in the range  $100\text{GeV}/c^2 < m_H < 150\text{GeV}/c^2$ , using neural networks optimized for each jet and tag bin independently. Using  $9.4\text{ }fb^{-1}$  of data, we obtain an expected (observed) limit on the Higgs boson production cross section of 10.1 (14.5) times the expected Standard Model value for a Higgs mass of  $115\text{ GeV}/c^2$ .

*Preliminary Results*

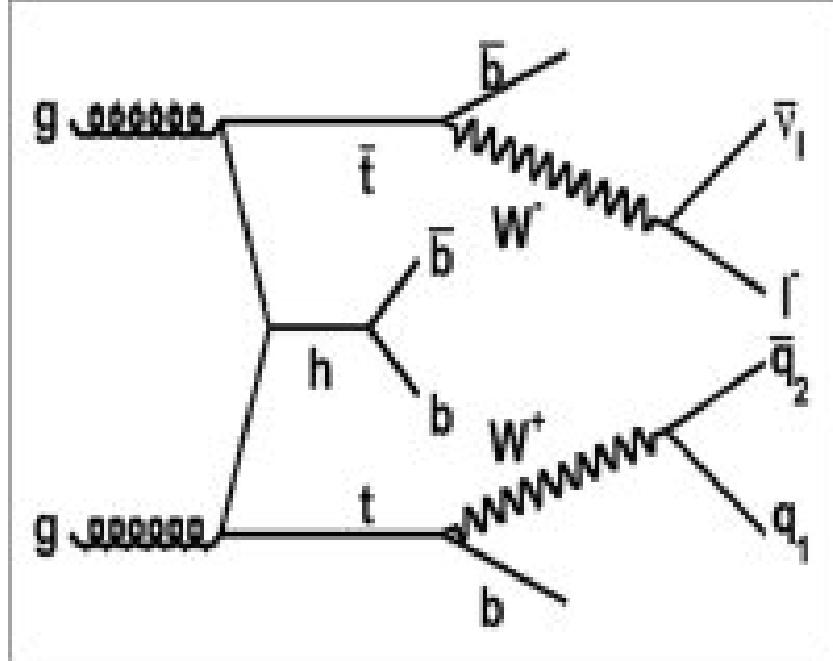
## Contents

<b>1</b>	<b>Introduction</b>	<b>3</b>
<b>2</b>	<b>Monte Carlo Samples</b>	<b>4</b>
<b>3</b>	<b>Data Samples</b>	<b>4</b>
<b>4</b>	<b>Event Selection</b>	<b>4</b>
4.1	Lepton Identification . . . . .	4
4.2	Missing Transverse Energy . . . . .	5
4.3	Jet Selection . . . . .	5
4.4	$b$ Tagging . . . . .	6
4.5	Predicted Backgrounds . . . . .	6
<b>5</b>	<b>Signal Discrimination</b>	<b>8</b>
<b>6</b>	<b>Systematic Uncertainties</b>	<b>24</b>
<b>7</b>	<b>Results</b>	<b>24</b>
7.1	Observed and Expected Limits . . . . .	25

# 1 Introduction

This note details a low mass Higgs boson search analysis using the process  $t\bar{t}H$ . The target sample is one lepton plus missing transverse energy plus at least 4 jets, with at least two of the jets  $b$  tagged. Although significant acceptance comes from the Higgs boson decay into two  $b$  quarks, there is no explicit requirement for this decay in this search. The overwhelming background to the process is standard model  $t\bar{t}$  production. Figure 1 shows a Feynman diagram of the  $t\bar{t}H$  process, assuming the Higgs decays to two  $b$  quarks.

The final state for this process is lepton plus jets, and as a result we use many of the techniques which have been developed for both the top group as well as the  $WH$  group. The basic strategy is to require a well identified high  $p_T$  lepton, significant missing transverse energy, and at least 4 jets. We also use two different algorithms to identify jets originating from a  $b$  quark. The SECVTX algorithm[2] identifies displaced vertices, and the Jet Probability algorithm[3] uses track impact parameters. We define 5 tagging samples, composed of various combinations and numbers of jets tagged by these two algorithms. For the purposes of this note, we have combined all of the 2-tag categories together and all of the 3-tag categories together for validation plots, but the categories are kept separate in the analysis.



**Figure 1:** The  $t\bar{t}H$  process.

Once our samples have been defined, we pass the selected events through a neural network discriminant. We use this discriminant to set 95% C.L. upper limits on the Higgs boson production cross section.

## 2 Monte Carlo Samples

Our Higgs boson signal model comes from the Monte Carlo samples generated with PYTHIA[5]. These Higgs boson samples were generated for a range of Higgs boson masses from  $100\text{GeV}/c^2$  to  $150\text{GeV}/c^2$  in increments of  $5\text{GeV}/c^2$ . Although we are searching for  $t\bar{t}H$  production, we do expect some acceptance from both  $WH$  and  $ZH$  events (primarily in the high background 4-jet bin), and these are included in our limit calculations described later. Note that the discriminant is trained using  $t\bar{t}H$  only for the signal.

The  $W$  and  $Z$  plus light-flavor and heavy-flavor jet processes are modeled using ALPGEN version 2.10[4] showered through PYTHIA. Likewise, the single-top contribution is modeled using parton-level events generated by MadEvent[6] and showered through PYTHIA. The rest of the background processes, including the  $t\bar{t}$ ,  $WW$ ,  $WZ$ , and  $ZZ$  processes were generated with PYTHIA. For backgrounds involving a top quark, the top mass was set to  $172.5\text{GeV}/c^2$ .

## 3 Data Samples

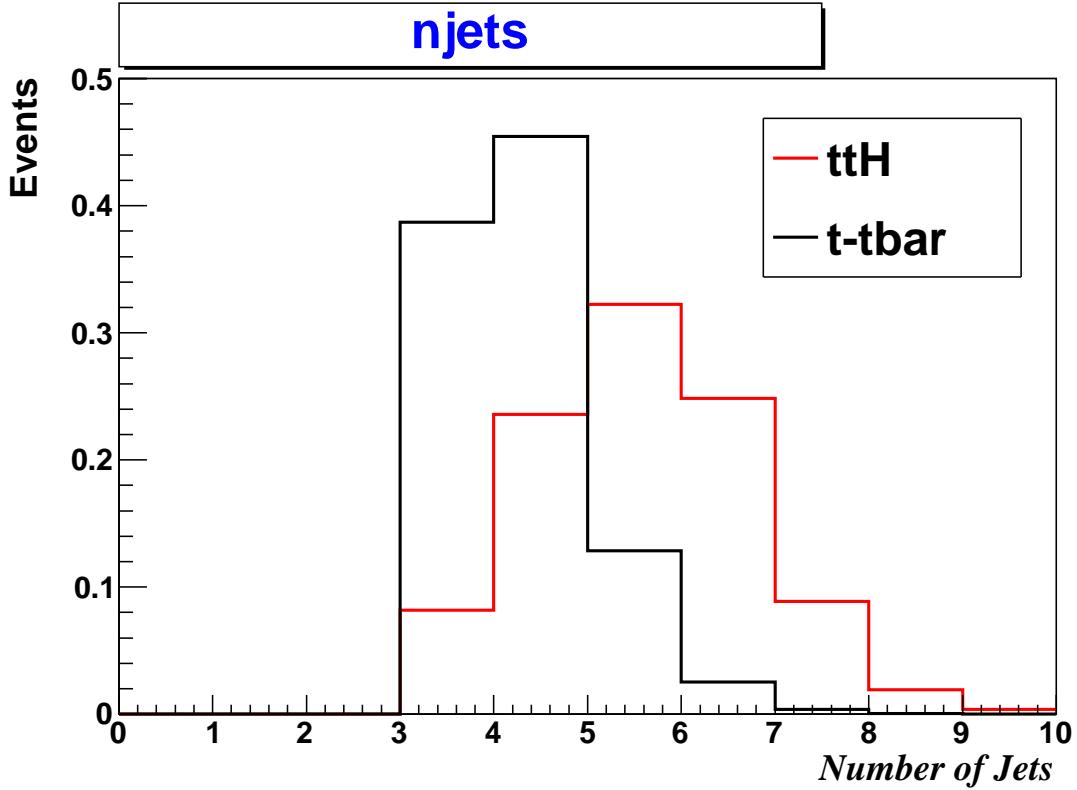
We use data taken by the CDF detector between February 2002 and September 2011, corresponding to an integrated luminosity of  $9.4\text{fb}^{-1}$ . We use data taken with four different triggers: the high  $p_T$  electron trigger, the plug electron trigger, the high  $p_T$  muon trigger, and the missing energy trigger. We use a standard CDF luminosity calculation[8], including corrections for the trigger system.

## 4 Event Selection

The basic strategy is the same as in the  $WH$  search[1], with the exception of requiring a higher jet multiplicity. We require a well identified high  $p_T$  lepton, significant missing energy, and at least 4 jets.

### 4.1 Lepton Identification

We use standard CDF definitions[1] for our lepton types: high  $p_T$  central electrons, high  $p_T$  plug electrons, and high  $p_T$  muons. For this analysis, we have added a fourth lepton category called “Iso Tracks”, which include a variety of muon types and isolated tracks, and which are required to pass three missing energy based triggers.



**Figure 2:** The distribution of the number of jets after all other cuts for  $t\bar{t}$  events versus  $t\bar{t}H$  events.

## 4.2 Missing Transverse Energy

$\cancel{E}_T$  is calculated according to standard CDF calculations[1] including corrections for vertex position, for the presence of muons, and for corrections to jet energies. We then select events with corrected  $\cancel{E}_T$  above  $20GeV$  for central electrons and Iso Tracks, above  $25GeV$  for plug electrons, and above  $10GeV$  for central muons.

## 4.3 Jet Selection

All jet energies are corrected according to standard CDF prescriptions. We then use jets with  $E_t \geq 20GeV$  and  $|\eta| \leq 2.0$ [1].

Figure 2 shows the distribution of the number of jets for  $t\bar{t}$  events versus  $t\bar{t}H$  events. For our final signal sample selection, we require that events have at least 4 jets. We further divide this sample into three categories, requiring exactly 4 jets, exactly 5 jets, and at least 6 jets.

## 4.4 $b$ Tagging

Our signal sample will contain 2 or 4 bottom quarks, depending on the Higgs boson decay. In addition, we can expect some tagging acceptance from  $\tau$  or charm decays of the  $W$  (either from the decay of the top quarks or  $H \rightarrow WW^*$ ). This leads us to require multiple tags in the final state. In addition, since different numbers of tags will in general have different signal to background ratios, we divide our sample based on the the number and types of tags observed. Events appear only once in each category, and are placed into the highest signal to background ratio category they satisfy. The following list is arranged in order of signal to background ratio:

**STSTST** These are events with at least 3 separate jets that are tagged by the SECVTX algorithm.

**STSTJP** These are events with exactly 2 jets that are tagged by the SECVTX algorithm, and at least 1 additional jet that is tagged by the Jet Probability algorithm.

**STJPJP** These are events with exactly 1 jet that is tagged by the SECVTX algorithm, and at least 2 additional jets that are tagged by the Jet Probability algorithm.

**STST** These are events with exactly 2 separate jets that are tagged by the SECVTX algorithm.

**STJP** These are events with exactly 1 jet that is tagged by the SECVTX, and exactly 1 additional jet that is tagged by the Jet Probability algorithm.

We will use “multiple-tagged” to refer to the combination of all of the above 5 separate tagging categories. We will used “2-tag” to refer to the combination of the STST and STJP categories and “3-tag” to refer to the combination of the STSTST, STSTJP, and STJPJP categories.

## 4.5 Predicted Backgrounds

The overwhelming background in this analysis is  $t\bar{t}$  events, predicted to be more than 85% of the selected sample. However, we will consider all of the backgrounds in the search, following the same methodology for background estimation as the  $WH$  search at CDF.

The backgrounds in order of size (summed over all 5  $b$ -tagging categories in the 5-jet bin):

**$t\bar{t} + \text{jets}$**  is modeled using POWHEG Monte Carlo with PYTHIA showering. This sample is expected to comprise  $\approx 90\%$  of the  $\geq 5$  jets multiple-tagged sample.

**$Wb\bar{b}$**  is modeled with ALPGEN v2 + PYTHIA Monte Carlo.

**Non- $W$**  is estimated according to the standard CDF prescriptions, by reversing any two of the lepton identification cuts.

Sample	$N_{\text{jets}} == 4$	$N_{\text{jets}} == 5$	$N_{\text{jets}} \geq 6$
DiTop	$27.52 \pm 6.78$	$10.61 \pm 2.6$	$3.73 \pm 0.88$
STopT	$0.17 \pm 0.04$	$0.06 \pm 0.01$	$0.01 \pm 0$
STopS	$0.13 \pm 0.03$	$0.05 \pm 0.01$	$0.01 \pm 0$
Wbb	$0.09 \pm 0.02$	$0.03 \pm 0.01$	$0 \pm 0$
Wcc	$0.03 \pm 0.01$	$0.01 \pm 0$	$0 \pm 0$
Wcj	$0 \pm 0$	$0 \pm 0$	$0 \pm 0$
Zjets	$0.06 \pm 0.01$	$0.02 \pm 0$	$0.01 \pm 0$
WW	$1.18 \pm 0.53$	$0.41 \pm 0.19$	$0.12 \pm 0.07$
WZ	$0.08 \pm 0.04$	$0.04 \pm 0.02$	$0.02 \pm 0.01$
ZZ	$0.03 \pm 0.01$	$0.01 \pm 0.01$	$0 \pm 0$
Mistags	$0.04 \pm 0.02$	$0.02 \pm 0.01$	$0.01 \pm 0$
Non-W	$0.43 \pm 2.5$	$0 \pm 0$	$0 \pm 0$
Total Prediction	$29.77 \pm 7.35$	$11.26 \pm 2.65$	$3.91 \pm 0.89$
ZH120	0.00	0.00	0.00
WH120	0.01	0.00	0.00
ttH120	0.09	0.20	0.27
Observed	31	16	8

**Table 1:** Background from various sources compared to observed data, for the STSTST tagging category.

**W + Charm** includes both  $Wc\bar{c}$  and  $Wc$ , and is modeled with ALPGEN v2 + PYTHIA Monte Carlo.

**Mistags** includes both  $W$  and  $Z$  plus light flavor jets. This contribution is estimated according to the standard CDF prescriptions, by applying the standard estimation of the tagging rate on light flavor jets to the  $W/Z$  + light flavor Monte Carlo.

**Single top** includes both s- and t-channel contributions and is modeled using MadEvent + PYTHIA Monte Carlo.

**Diboson** includes  $WW$ ,  $WZ$ , and  $ZZ$ , and is modeled using PYTHIA Monte Carlo.

**Z + jets** includes both  $Zb\bar{b}$  and  $Zc\bar{c}$  and is modeled with ALPGEN v2 + PYTHIA Monte Carlo.

Sample	$N_{\text{jets}} == 4$	$N_{\text{jets}} == 5$	$N_{\text{jets}} \geq 6$
DiTop	$65.11 \pm 13.88$	$24.64 \pm 5.48$	$8 \pm 1.78$
STopT	$0.41 \pm 0.1$	$0.12 \pm 0.03$	$0.03 \pm 0.01$
STopS	$0.38 \pm 0.1$	$0.11 \pm 0.03$	$0.03 \pm 0.01$
Wbb	$0.14 \pm 0.03$	$0.03 \pm 0.01$	$0.01 \pm 0$
Wcc	$0.07 \pm 0.02$	$0.02 \pm 0$	$0 \pm 0$
Wcj	$0.01 \pm 0$	$0 \pm 0$	$0 \pm 0$
Zjets	$0.17 \pm 0.02$	$0.06 \pm 0.01$	$0.02 \pm 0$
WW	$2.83 \pm 1.25$	$0.92 \pm 0.42$	$0.33 \pm 0.15$
WZ	$0.44 \pm 0.21$	$0.16 \pm 0.08$	$0.07 \pm 0.04$
ZZ	$0.16 \pm 0.07$	$0.05 \pm 0.02$	$0.01 \pm 0.01$
Mistags	$0.21 \pm 0.09$	$0.09 \pm 0.04$	$0.03 \pm 0.02$
Non-W	$1.83 \pm 2.78$	$0 \pm 0$	$0 \pm 0$
Total Prediction	$71.75 \pm 14.51$	$26.18 \pm 5.58$	$8.53 \pm 1.82$
ZH120	0.03	0.00	0.00
WH120	0.10	0.01	0.00
ttH120	0.06	0.19	0.23
Observed	58	18	15

**Table 2:** Background from various sources compared to observed data, for the STSTJP tagging category.

## 5 Signal Discrimination

In order to discriminate the signal from the backgrounds, we employ a neural network to classify  $t\bar{t}$  and  $t\bar{t}H$ . The network is trained with 18 input variables, 15 hidden nodes in a single hidden layer, and one output node, trained using JetNet. Since the overwhelming background to the  $t\bar{t}H$  process is  $t\bar{t}$ , we look for variables which can distinguish these two processes. The variables we consider are:

- $\cancel{E}_T$  corrected as described in section 4.2
- Maximum Jet  $E_T$
- Mean Jet  $E_T$
- Event Mass
- Event sum  $E_T$
- $H_T$
- Number of Loose jets

Sample	$N_{\text{jets}} == 4$	$N_{\text{jets}} == 5$	$N_{\text{jets}} \geq 6$
DiTop	$40.48 \pm 6.68$	$16.14 \pm 3$	$5.33 \pm 1.12$
STopT	$0.26 \pm 0.05$	$0.08 \pm 0.02$	$0.02 \pm 0$
STopS	$0.23 \pm 0.05$	$0.08 \pm 0.02$	$0.02 \pm 0.01$
Wbb	$0.1 \pm 0.03$	$0.06 \pm 0.02$	$0.01 \pm 0$
Wcc	$0.05 \pm 0.01$	$0.01 \pm 0$	$0 \pm 0$
Wcj	$0 \pm 0$	$0 \pm 0$	$0 \pm 0$
Zjets	$0.15 \pm 0.02$	$0.06 \pm 0.01$	$0.02 \pm 0$
WW	$1.97 \pm 0.87$	$0.69 \pm 0.31$	$0.22 \pm 0.1$
WZ	$0.7 \pm 0.32$	$0.27 \pm 0.13$	$0.12 \pm 0.06$
ZZ	$0.25 \pm 0.11$	$0.08 \pm 0.04$	$0.03 \pm 0.01$
Mistags	$0.4 \pm 0.19$	$0.16 \pm 0.08$	$0.05 \pm 0.03$
Non-W	$0.95 \pm 2.53$	$0 \pm 0$	$0 \pm 0$
Total Prediction	$45.56 \pm 7.41$	$17.63 \pm 3.11$	$5.82 \pm 1.16$
ZH120	0.00	0.00	0.00
WH120	0.02	0.00	0.00
ttH120	0.05	0.09	0.12
Observed	47	22	8

**Table 3:** Background from various sources compared to observed data, for the STJPJP tagging category.

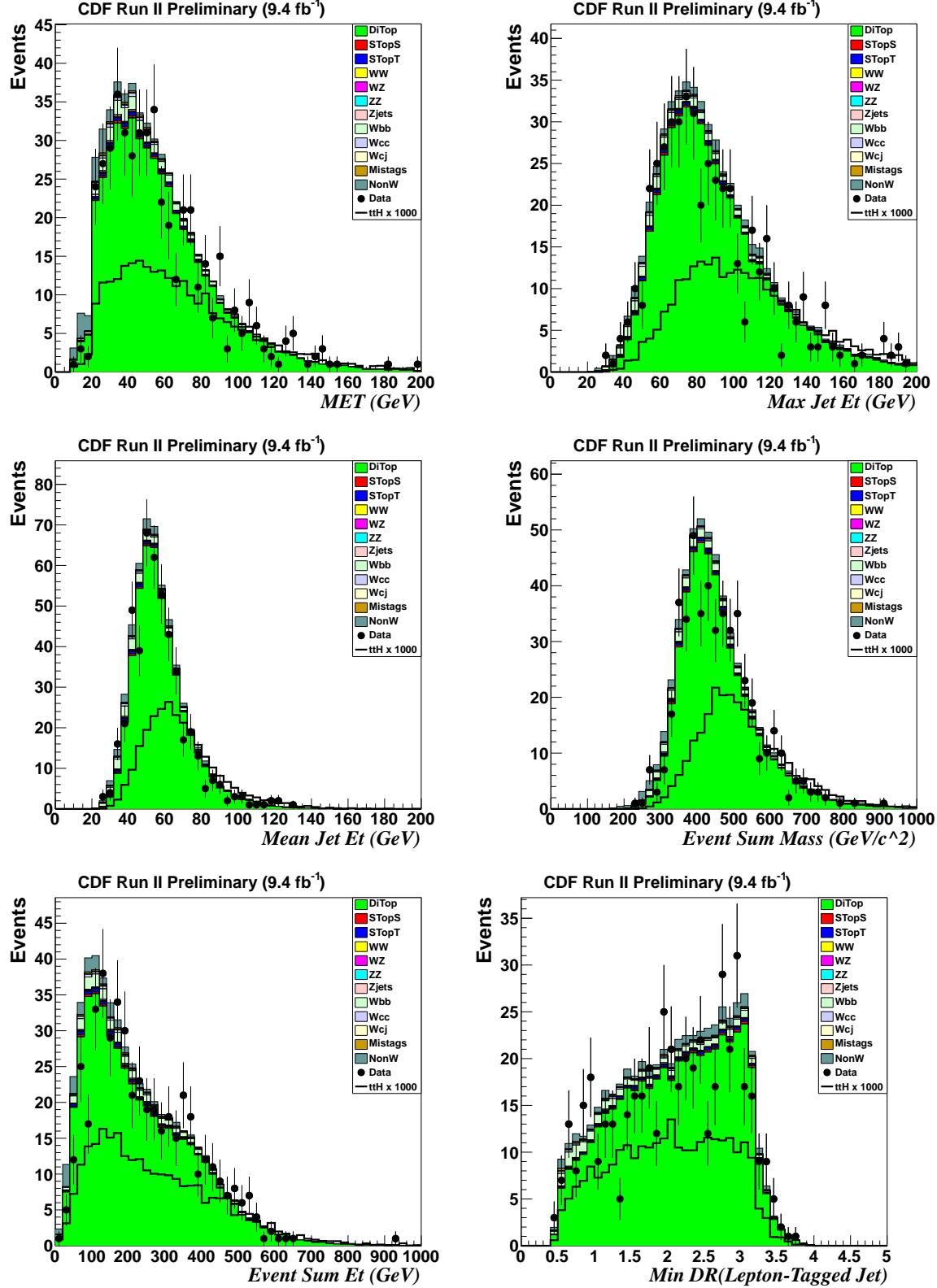
- Minimum  $\Delta R$  between tagged jets
- Jet 2  $E_T$
- Jet 3  $E_T$
- $\Delta\phi$  between lepton and the  $\cancel{E}_T$
- Maximum Tagged Jet  $E_T$
- $W$  Transverse Mass
- Lepton plus nearest jet mass
- Summed  $E_T$  of tight jets
- Minimum dijet mass
- Dijet mass of untagged jets
- Dijet mass of highest  $E_T$  tagged jets

Sample	$N_{\text{jets}} == 4$	$N_{\text{jets}} == 5$	$N_{\text{jets}} \geq 6$
DiTop	$414.99 \pm 35.52$	$125.21 \pm 11$	$32.19 \pm 2.93$
STopT	$3.48 \pm 0.29$	$0.69 \pm 0.06$	$0.12 \pm 0.01$
STopS	$4.69 \pm 0.5$	$0.95 \pm 0.11$	$0.17 \pm 0.02$
Wbb	$2.14 \pm 0.48$	$0.59 \pm 0.13$	$0.11 \pm 0.03$
Wcc	$0.81 \pm 0.11$	$0.18 \pm 0.02$	$0.05 \pm 0.01$
Wcj	$0.09 \pm 0.01$	$0.01 \pm 0$	$0 \pm 0$
Zjets	$3.37 \pm 0.35$	$0.82 \pm 0.09$	$0.17 \pm 0.02$
WW	$29.35 \pm 12.62$	$6.77 \pm 2.99$	$1.9 \pm 0.85$
WZ	$12.66 \pm 5.55$	$3.32 \pm 1.51$	$1.04 \pm 0.48$
ZZ	$4.47 \pm 1.95$	$0.99 \pm 0.45$	$0.23 \pm 0.1$
Mistags	$11.9 \pm 4.01$	$3.13 \pm 1.22$	$0.76 \pm 0.39$
Non-W	$23.15 \pm 19.52$	$0 \pm 0$	$0 \pm 0$
Total Prediction	$511.08 \pm 46.38$	$142.66 \pm 12.37$	$36.72 \pm 3.33$
ZH120	0.0	0.00	0.00
WH120	0.03	0.01	0.01
ttH120	0.1	0.19	0.23
Observed	545	162	41

**Table 4:** Background from various sources compared to observed data, for the STJP tagging category.

Validation plots of these variables are shown for the STST category, in figures 3, 4, and 5 for the 4-jet only bin, in figures 6, 7, and 8 for the 5-jet only bin, and in figures 9, 10, and 11 for the  $\geq 6$ -jet bin.

The final discriminants are shown in figures 12 for 4 jet events, 13 for 5 jets events, and 14 for  $\geq 6$  jets events.



**Figure 3:** Neural Network input variables,  $\text{njets}==4$ , STST category.

Sample	$N_{\text{jets}} == 4$	$N_{\text{jets}} == 5$	$N_{\text{jets}} \geq 6$
DiTop	$426.44 \pm 50.5$	$121.35 \pm 13.45$	$28.54 \pm 2.86$
STopT	$3.67 \pm 0.43$	$0.65 \pm 0.07$	$0.1 \pm 0.01$
STopS	$5.21 \pm 0.72$	$0.9 \pm 0.12$	$0.14 \pm 0.02$
Wbb	$0.98 \pm 0.17$	$0.22 \pm 0.04$	$0.06 \pm 0.01$
Wcc	$0.59 \pm 0.08$	$0.11 \pm 0.02$	$0.02 \pm 0$
Wcj	$0.11 \pm 0.01$	$0.02 \pm 0$	$0 \pm 0$
Zjets	$2.06 \pm 0.2$	$0.51 \pm 0.05$	$0.09 \pm 0.01$
WW	$25.49 \pm 10.97$	$5.47 \pm 2.41$	$1.35 \pm 0.62$
WZ	$4.02 \pm 1.76$	$1.05 \pm 0.48$	$0.34 \pm 0.16$
ZZ	$1.42 \pm 0.62$	$0.31 \pm 0.14$	$0.07 \pm 0.04$
Mistags	$3.11 \pm 1$	$0.87 \pm 0.33$	$0.21 \pm 0.1$
Non-W	$19.25 \pm 16.4$	$0 \pm 0$	$0 \pm 0$
Total Prediction	$492.35 \pm 56.08$	$131.47 \pm 14.03$	$30.93 \pm 3.01$
ZH120	0.06	0.01	0.00
WH120	0.29	0.04	0.01
ttH120	0.27	0.37	0.37
Observed	475	162	43

**Table 5:** Background from various sources compared to observed data, for the STST tagging category.

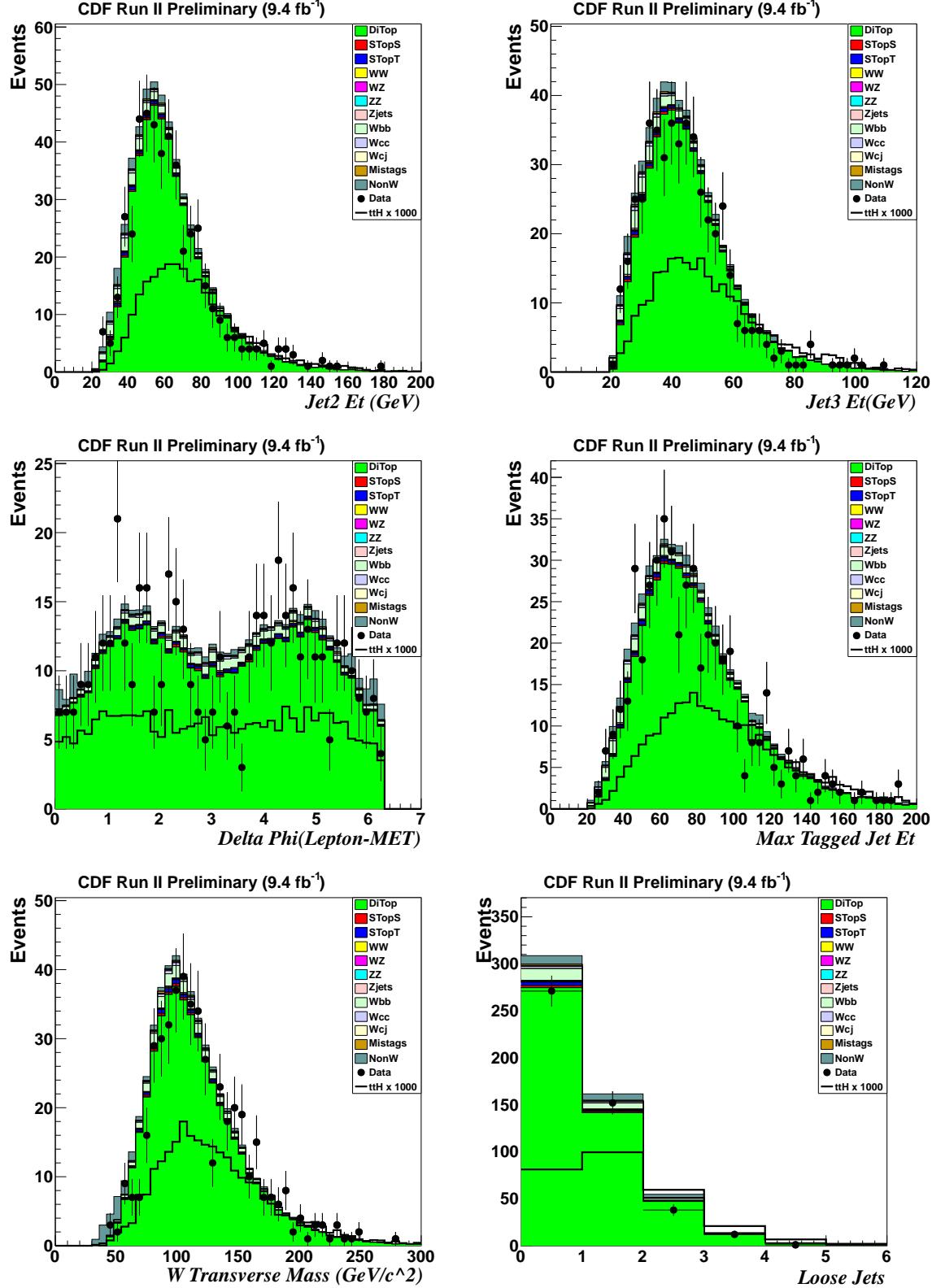


Figure 4: Neural Network input variables,  $N_{\text{jets}} = 4$ , STST category.

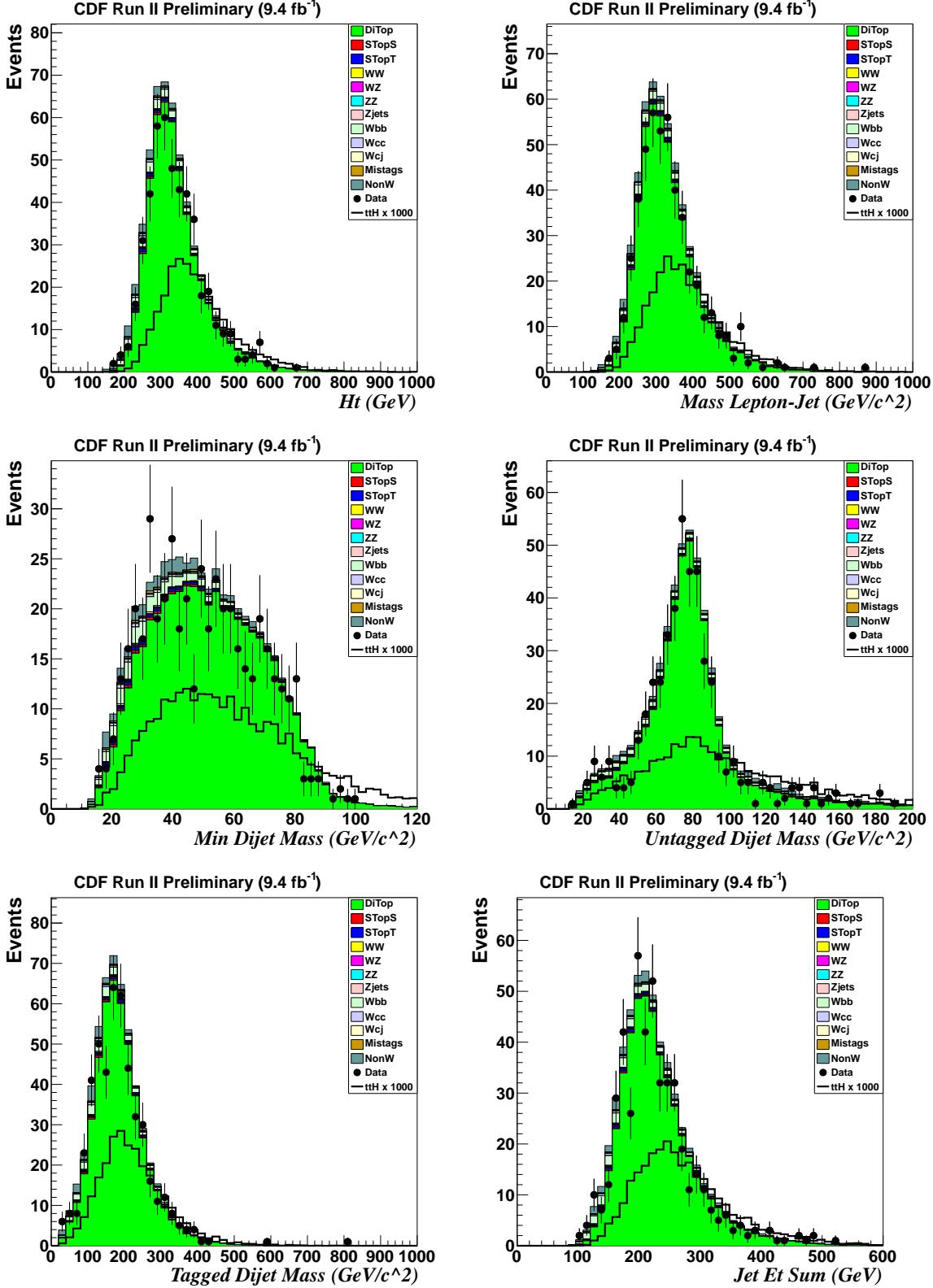


Figure 5: Neural Network input variables,  $N_{\text{jets}} = 4$ , STST category.

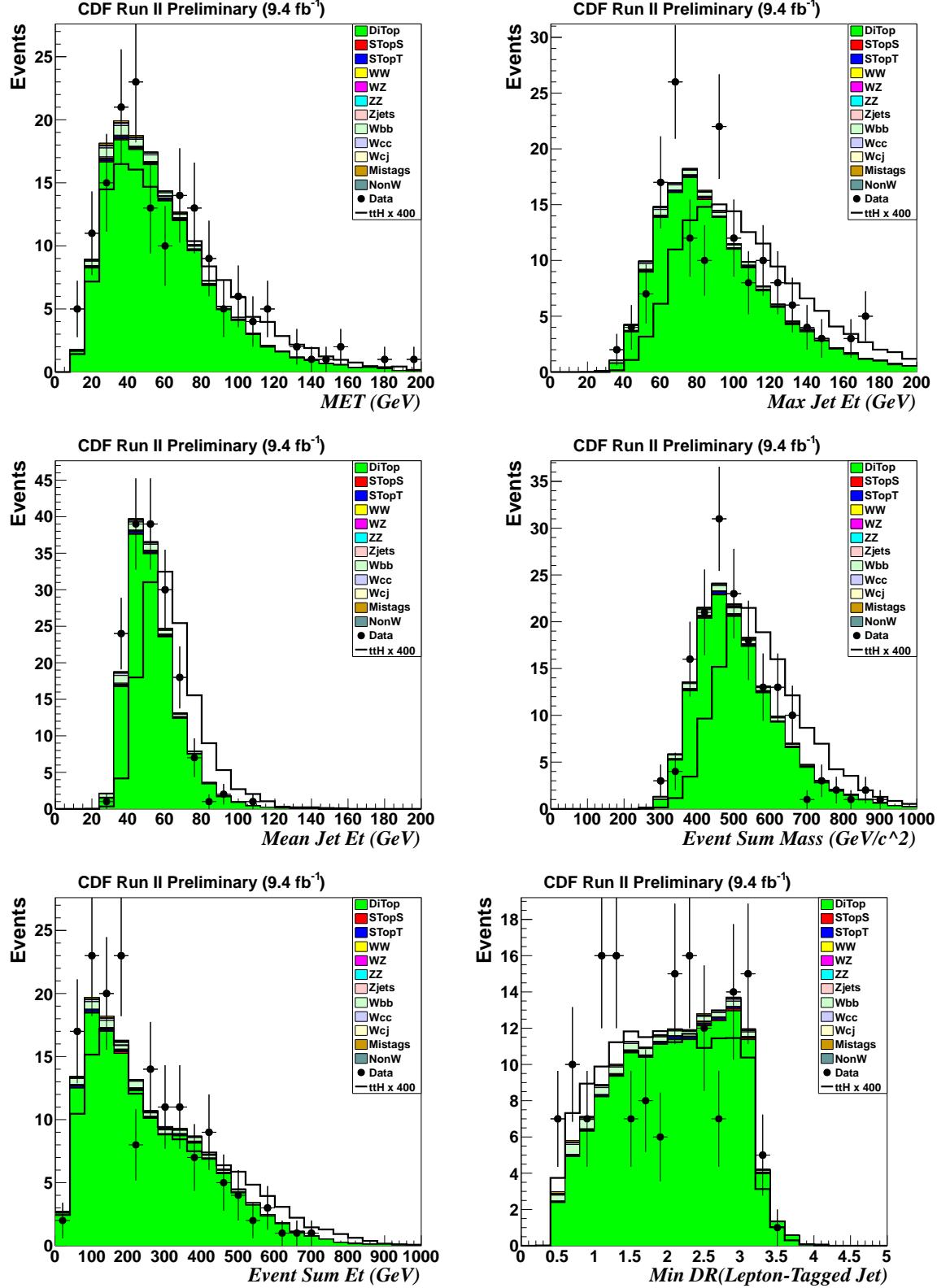


Figure 6: Neural Network input variables,  $N_{\text{jets}} = 5$ , STST category.

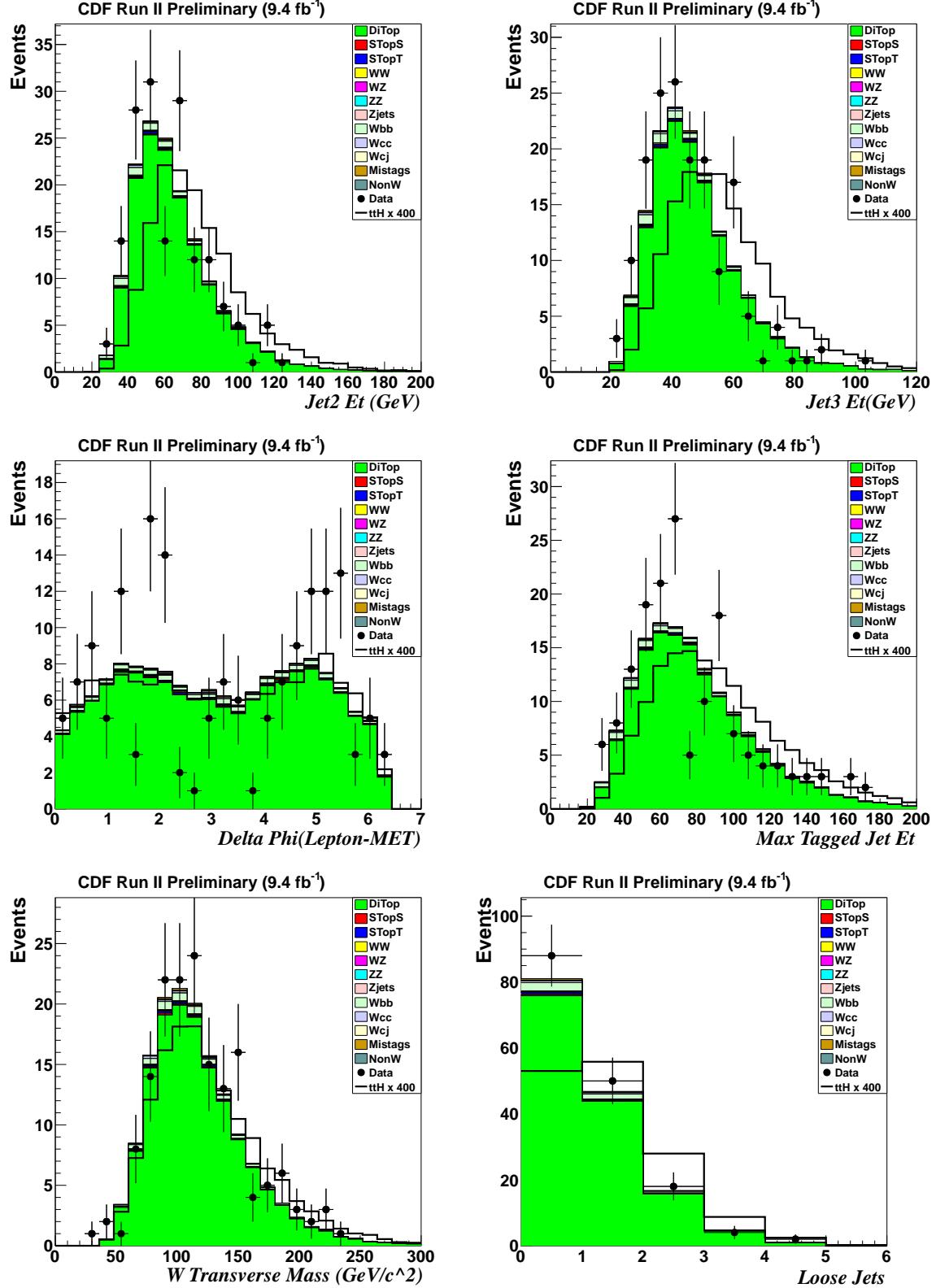


Figure 7: Neural Network input variables,  $N_{\text{jets}} = 5$ , STST category.

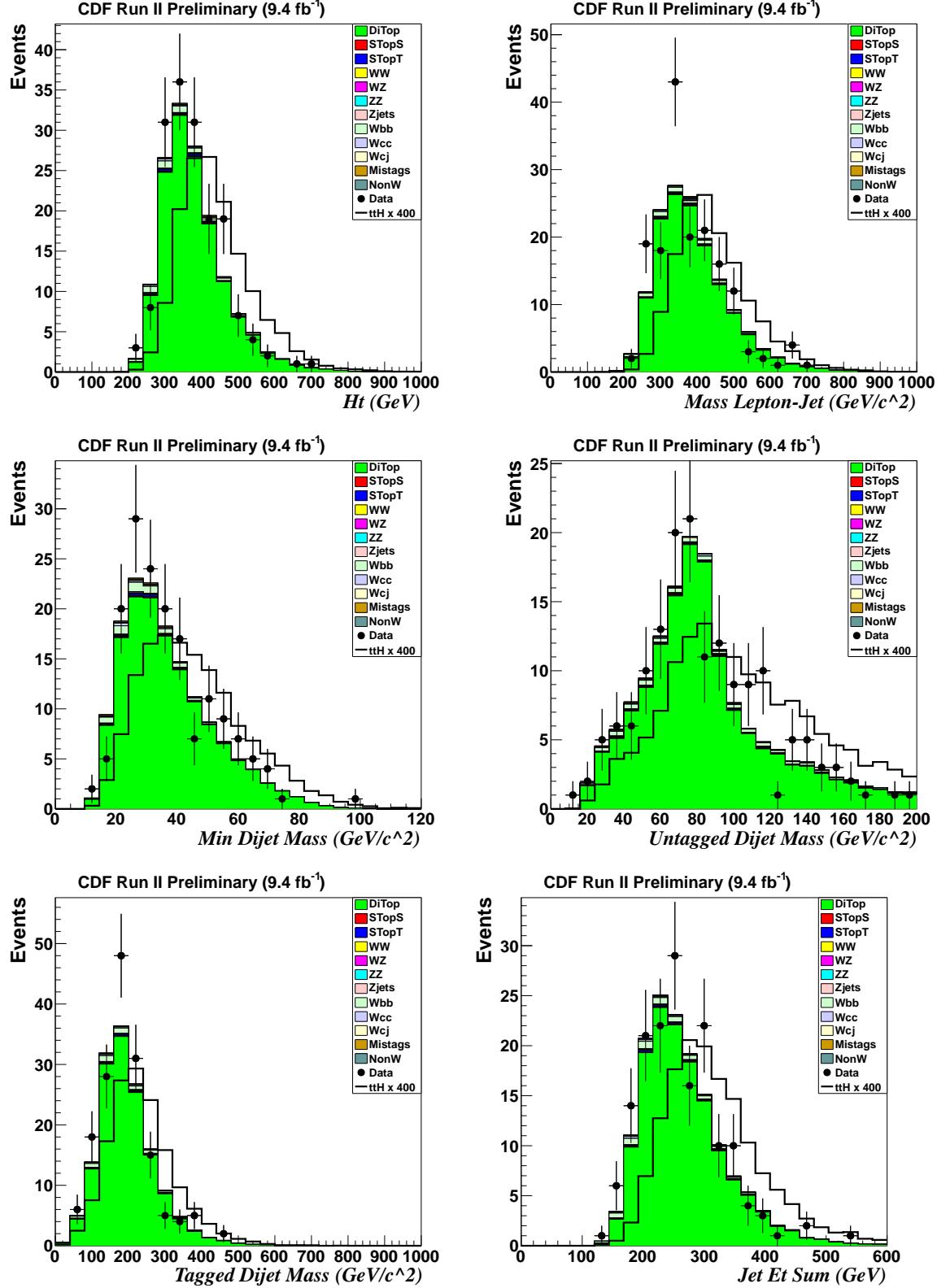


Figure 8: Neural Network input variables,  $N_{\text{jets}} = 5$ , STST category.

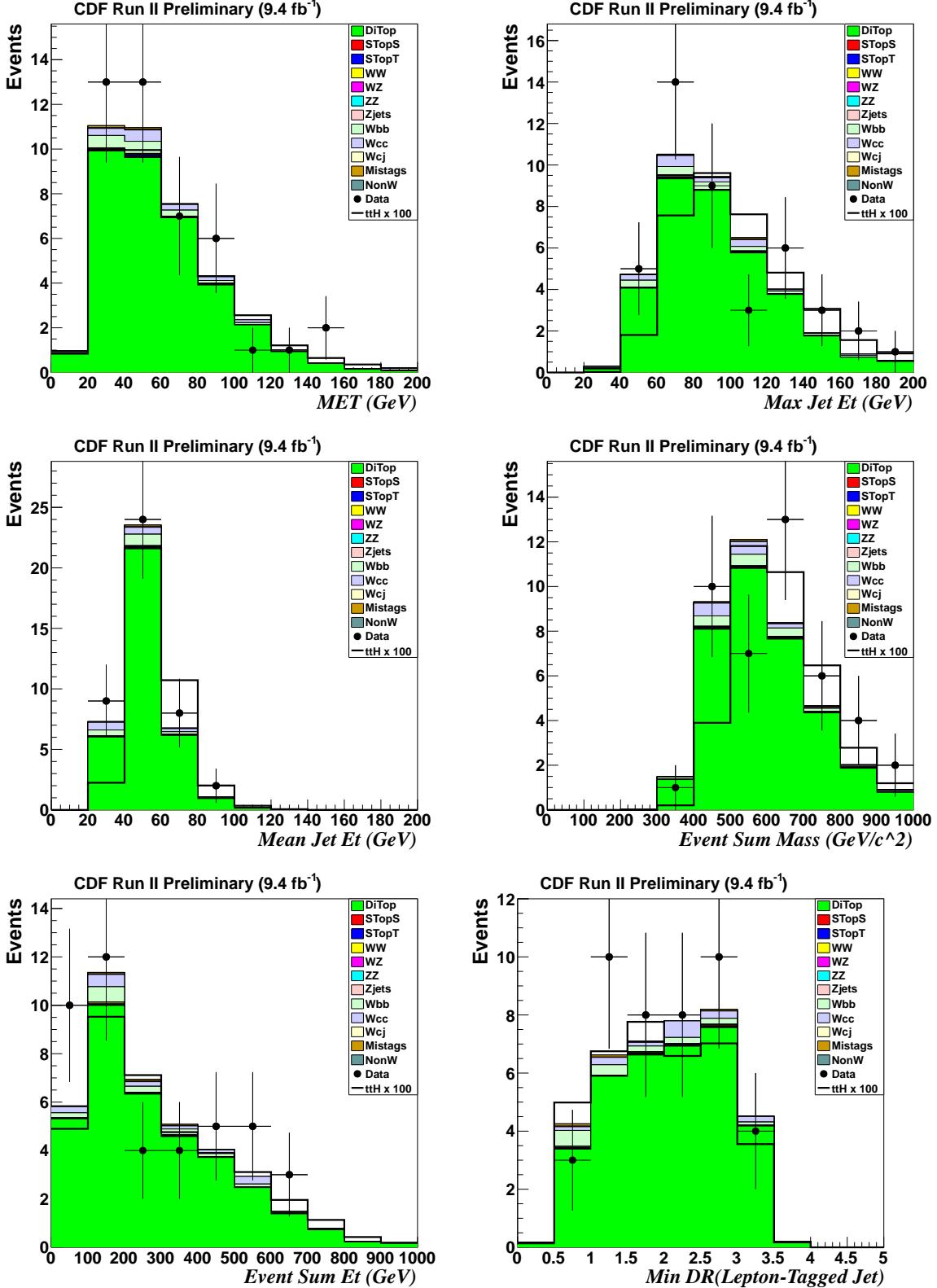
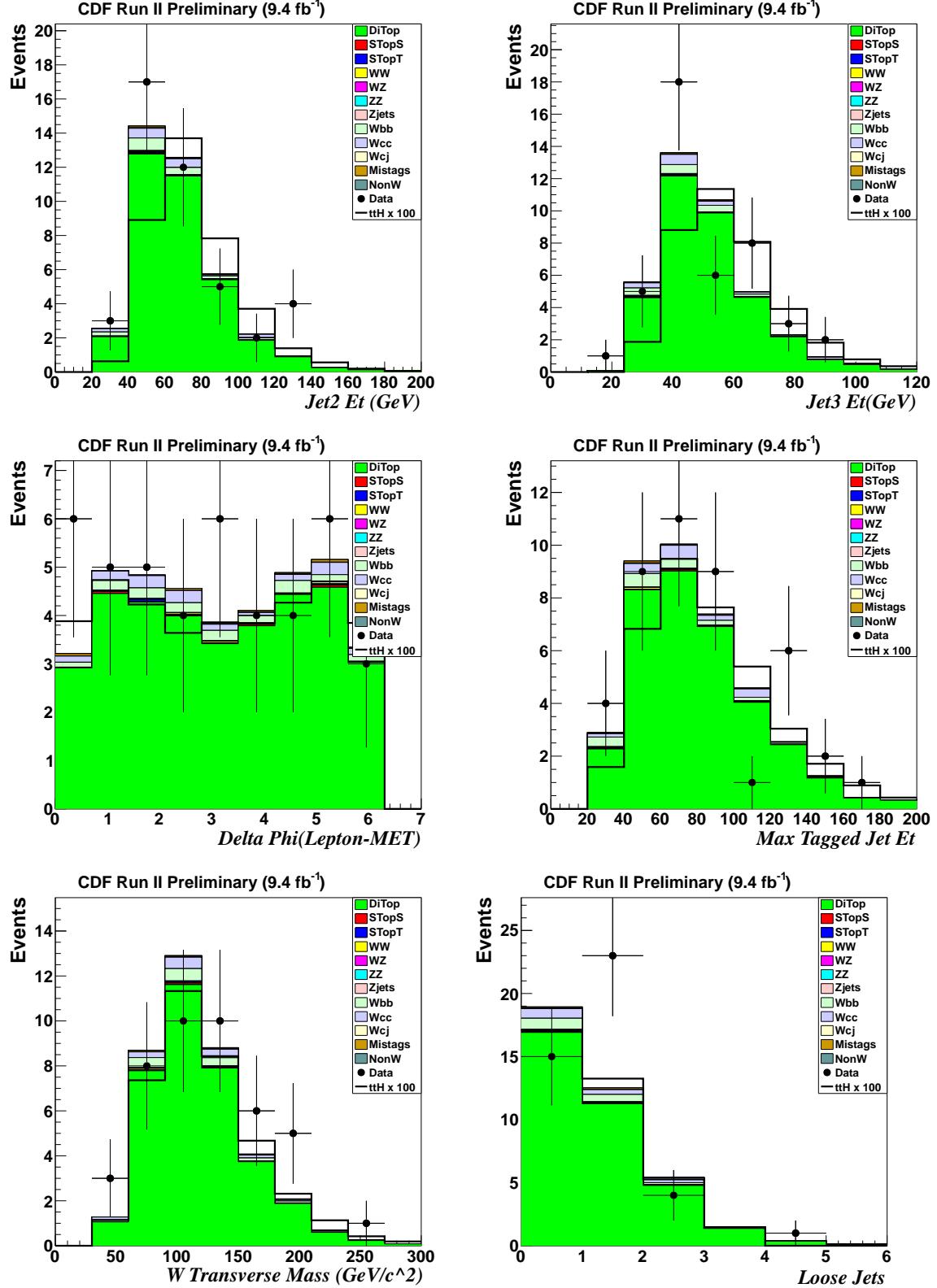


Figure 9: Neural Network input variables,  $N_{\text{jets}} \geq 6$ , STST category.



**Figure 10:** Neural Network input variables,  $N_{\text{jets}} \geq 6$ , STST category.

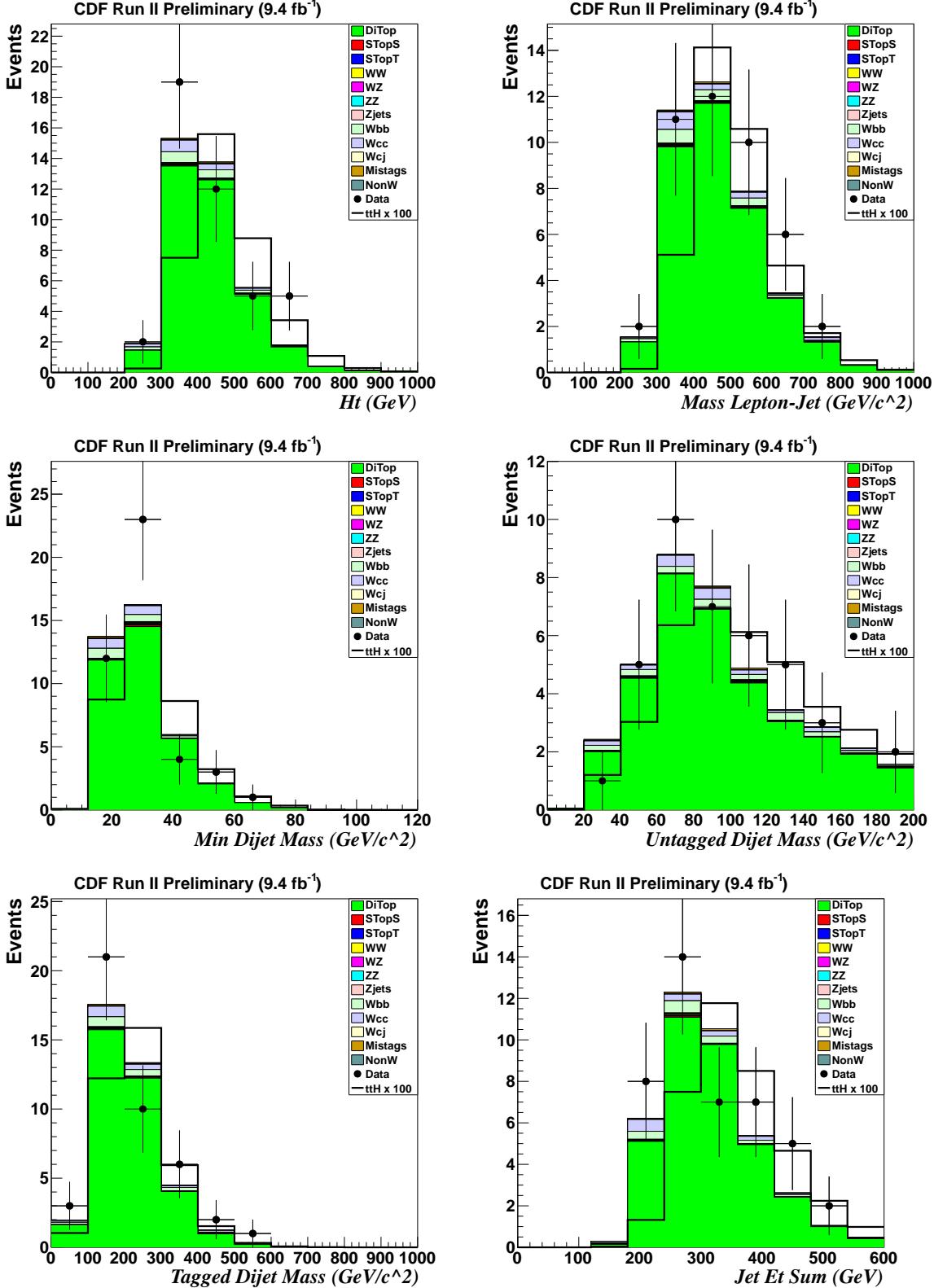
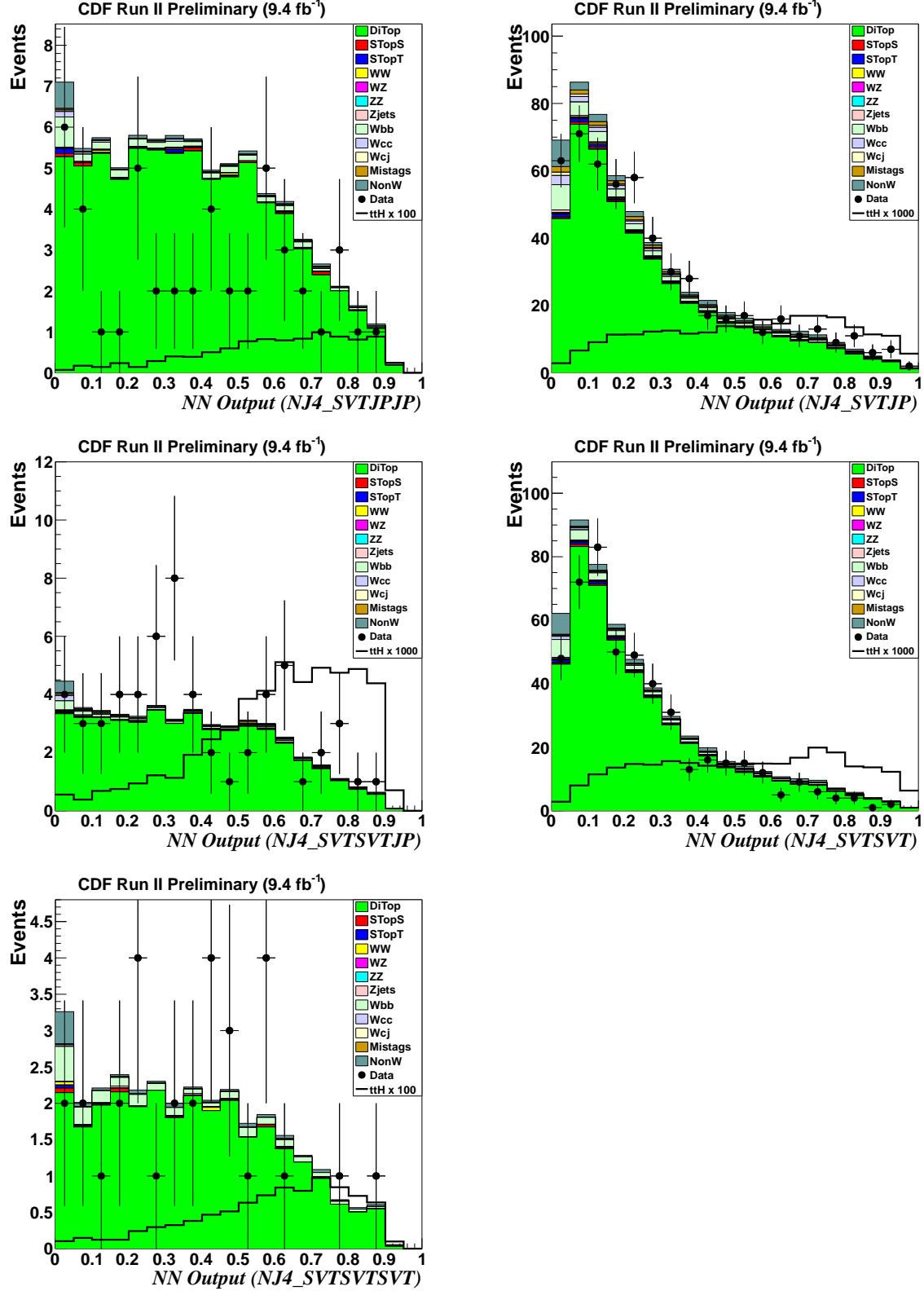


Figure 11: Neural Network input variables,  $N_{\text{jets}} \geq 6$ , STST category.



**Figure 12:** Neural Network output discriminant for all 5 tag categories,  $N_{\text{jets}} = 4$ .

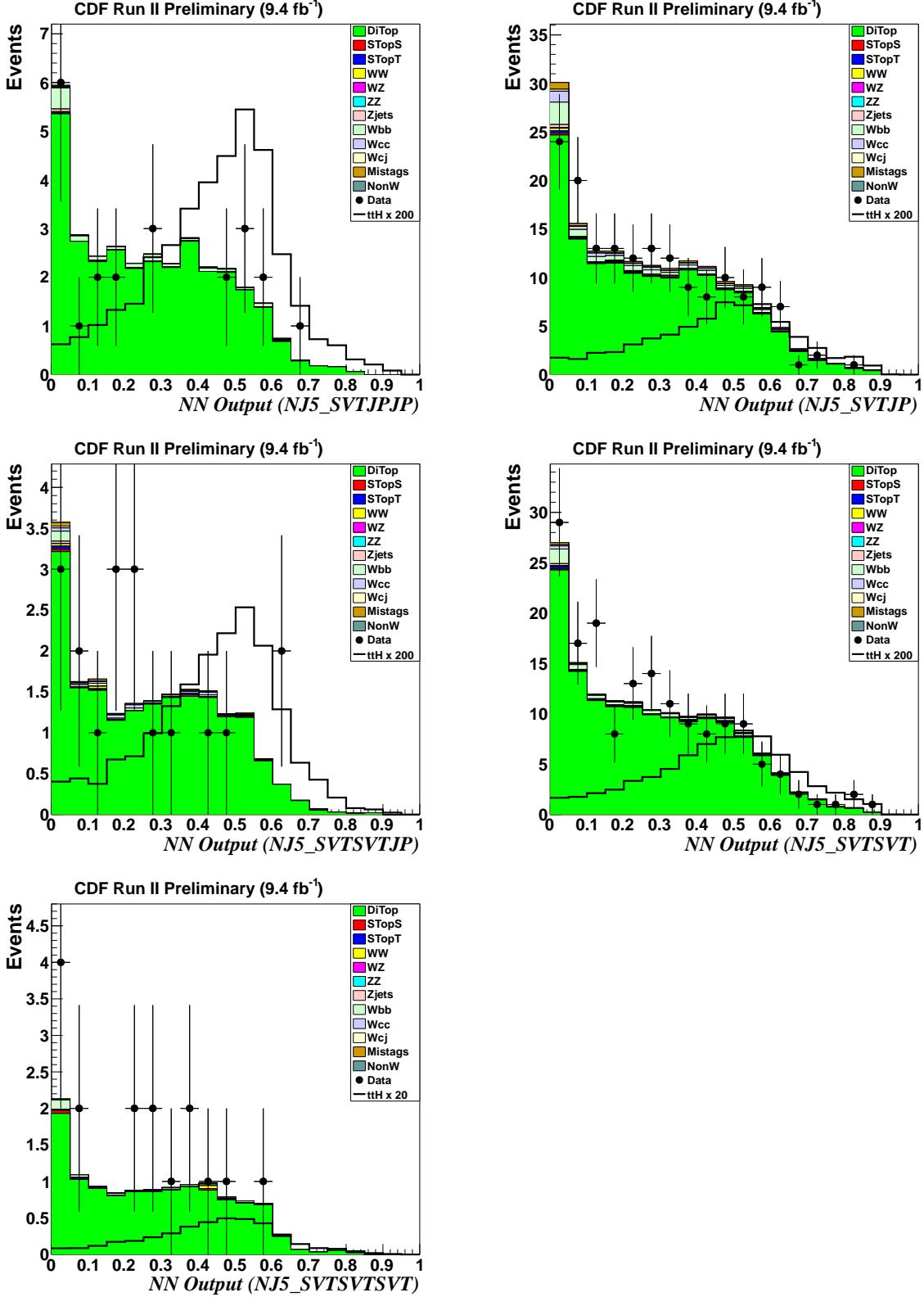
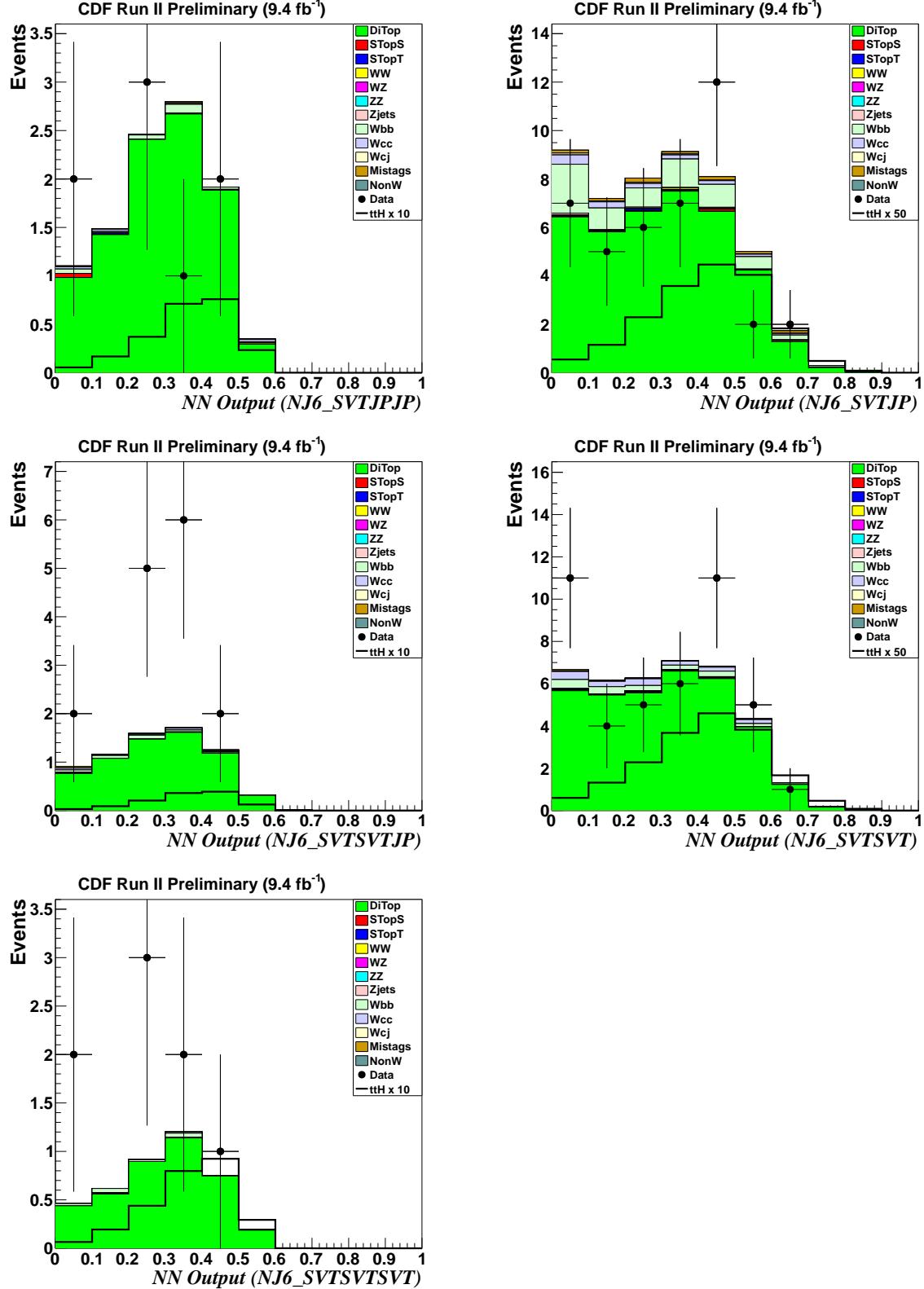


Figure 13: Neural Network output discriminant for all 5 tag categories,  $N_{\text{jets}} = 5$ .



**Figure 14:** Neural Network output discriminant for all 5 tag categories,  $N_{\text{jets}} \geq 6$ .

4 jets	STJP		STJPJP		STST		STSTJP		STSTST	
	$t\bar{t}$	$t\bar{t}H$								
$t\bar{t}H$ cross section	0	10	0	10	0	10	0	10	0	10
$t\bar{t}$ cross section	10	0	10	0	10	0	10	0	10	0
Tevatron luminosity	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8
CDF luminosity	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4

**Table 6:** Rate systematic uncertainties which are common across all jet multiplicities.

## 6 Systematic Uncertainties

This analysis includes many of the same systematics that are used in the  $WH$  analysis. The major systematics include the uncertainties on the process cross sections and the jet energy scale (JES) systematic, which can strongly affect the number of jets in an event. This JES systematic not only affects the rate of the various processes, but also the shape of the discriminants.

Other important systematics are the uncertainty on the  $b$ -tag scale factors which account for the difference between the  $b$ -tag rates for Monte Carlo and for data, the uncertainty on the measurement of the luminosity delivered to CDF, and the uncertainty on the amount of initial and final state radiation (ISR/FSR), which we apply to both the dominant  $t\bar{t}$  background and to the signal.

Table 6 shows the rate systematics which are common across all jet multiplicity bins. These include the  $t\bar{t}$  and  $t\bar{t}H$  production cross section uncertainties, and the luminosity uncertainties for CDF and the Tevatron. Tables 7, 8, and 9 summarize the various jet-bin dependent systematics applied to the  $t\bar{t}$  background as well as the signal. Because the total rate of the other backgrounds is so small, we do not show the effects of the systematics that we apply to them. Uncertainties shown are relative, in percent, and are symmetric unless otherwise indicated.

## 7 Results

Using the outputs of the final event discriminants described above, we observe no evidence of a  $t\bar{t}H$  signal and proceed to set limits on the Higgs production cross section for this channel. We use the MCLimit machinery[7] to produce median,  $\pm 1\sigma$ , and  $\pm 2\sigma$  expected limits, along with the observed limits. This is done for  $100GeV/c^2 \leq m_H \leq 145GeV/c^2$  in steps of  $5GeV/c^2$ . We use 15 different MCLimit channels: one for each tagging category, separated into 4, 5, and  $\geq 6$  jets.

### 7.1 Observed and Expected Limits

The expected and observed limits are shown in table 11 and figure 15.

4 jets	STJP		STJPJP		STST		STSTJP		STSTST	
	$t\bar{t}$	$t\bar{t}H$								
$b$ -tag scale factor +	1.79	-0.23	4.77	-1.74	9.09	7.50	14.42	5.14	14.79	15.46
$b$ -tag scale factor -	-1.89	-0.86	-4.75	-1.84	-9.75	-5.98	-9.41	-6.72	-19.02	-14.28
light jet tag rate+	1.89	1.09	12.41	5.14	-0.27	-0.14	9.61	1.92	2.99	1.13
light jet tag rate-	-0.72	-0.11	-6.71	-4.84	0.64	0.39	-3.56	-1.75	-5.14	-1.37
jet energy scale+	2.77	-8.80	3.57	-8.33	2.52	-9.06	3.77	-9.77	1.48	-5.66
jet energy scale-	-4.38	8.06	-0.33	11.92	-3.80	7.42	-0.48	8.77	-2.61	6.74
ISR/FSR	0.36	3.04	0.38	0.75	1.29	2.73	3.86	5.28	0.33	5.13

**Table 7:** Systematic uncertainties in events with 4 jets. The  $b$ -tag scale factor, light jet tag rate, and jet energy scale systematics are all shape+rate systematics, but only the rate portion is shown here. ISR/FSR refers to initial and final state radiation, and is a rate only systematic.

5 jets	STJP		STJPJP		STST		STSTJP		STSTST	
	$t\bar{t}$	$t\bar{t}H$								
$b$ -tag scale factor +	1.25	-1.96	1.99	-0.99	8.69	5.80	11.36	4.48	14.94	12.96
$b$ -tag scale factor -	-0.55	2.06	-5.21	0.89	-9.74	-7.30	-12.13	-4.50	-16.28	-15.87
light jet tag rate+	2.81	1.96	12.47	1.19	-1.94	-0.57	10.70	0.87	4.02	1.15
light jet tag rate-	-0.78	-0.66	-11.50	-2.53	0.92	-0.77	-7.19	-2.66	-9.48	-0.23
jet energy scale+	14.48	-1.02	9.96	-0.64	11.84	-2.21	13.07	-3.40	6.51	-3.12
jet energy scale-	-11.71	2.51	-12.79	-1.34	-13.49	0.66	-9.15	1.48	-7.57	2.45
ISR/FSR	3.42	2.41	11.28	0.79	5.24	2.30	3.89	3.26	3.95	2.88

**Table 8:** Systematic uncertainties in events with 5 jets. The  $b$ -tag scale factor, light jet tag rate, and jet energy scale systematics are all shape+rate systematics, but only the rate portion is shown here. ISR/FSR refers to initial and final state radiation, and is a rate only systematic.

$\geq 6$ jets	STJP		STJPJP		STST		STSTJP		STSTST	
	$t\bar{t}$	$t\bar{t}H$								
$b$ -tag scale factor +	1.52	-2.07	4.07	-0.89	9.02	4.27	17.30	4.78	12.00	13.13
$b$ -tag scale factor -	-1.47	1.85	-1.53	2.99	-8.39	-8.07	-8.32	-3.91	-14.59	-12.00
light jet tag rate +	1.76	1.72	17.63	4.43	-1.46	-2.55	15.68	2.25	8.47	-0.12
light jet tag rate -	-2.29	0.21	-16.95	-3.03	2.68	-1.33	-12.32	0.98	-11.76	-2.05
jet energy scale+	25.07	12.17	17.29	11.78	25.58	10.81	26.49	10.02	23.29	8.58
jet energy scale-	-21.07	-12.62	-20.68	-9.86	-22.19	-13.16	-17.30	-8.69	-19.76	-11.05
ISR/FSR	13.17	0.75	17.33	2.32	12.38	1.42	20.89	1.15	14.84	0.38

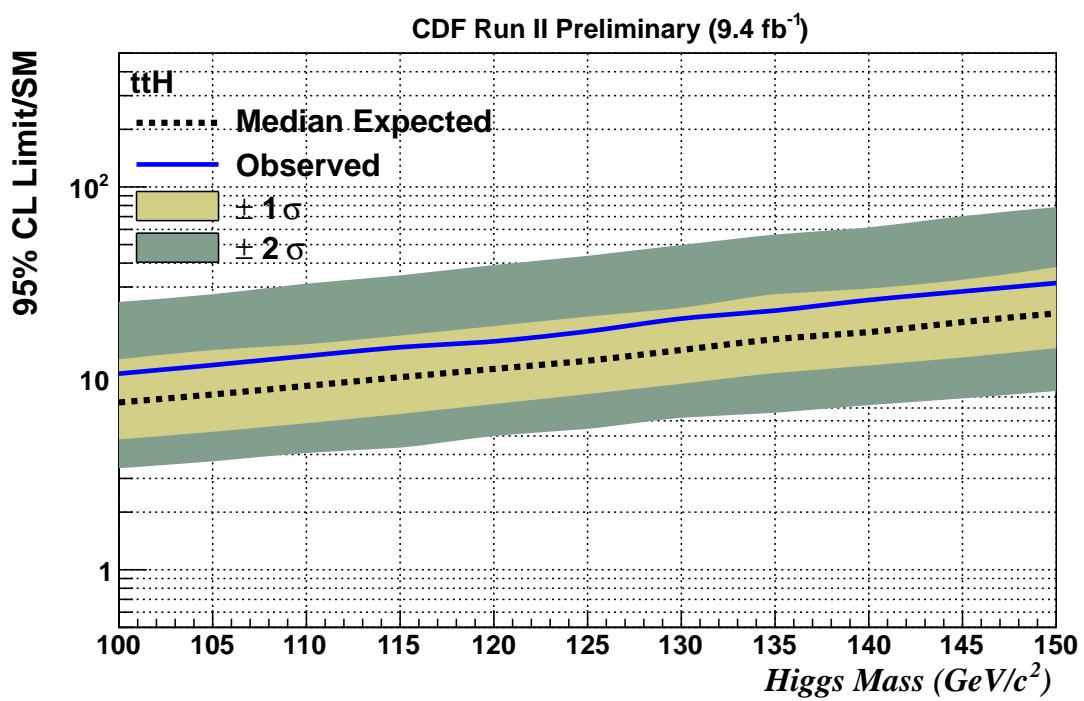
**Table 9:** Systematic uncertainties in events with  $\geq 6$  jets. The  $b$ -tag scale factor, light jet tag rate, and jet energy scale systematics are all shape+rate systematics, but only the rate portion is shown here. ISR/FSR refers to initial and final state radiation, and is a rate only systematic.

Higgs Mass	$t\bar{t}H$ Cross section (fb)
100	7.99
110	6.28
120	4.94
130	3.88
140	3.05

**Table 10:** Cross sections at  $\sqrt{s} = 1.96 \text{ TeV}$  for  $t\bar{t}H$

$m_H$	Obs	$-2\sigma$	$-1\sigma$	Exp	$+1\sigma$	$+2\sigma$
100	<b>10.6</b>	3.39	4.80	<b>7.48</b>	12.57	25.09
105	<b>11.7</b>	3.68	5.26	<b>8.23</b>	14.04	27.52
110	<b>13.1</b>	4.08	5.83	<b>9.13</b>	15.08	31.25
115	<b>14.5</b>	4.34	6.52	<b>10.14</b>	16.74	34.51
120	<b>15.6</b>	4.99	7.34	<b>11.20</b>	18.75	39.10
125	<b>17.6</b>	5.44	8.28	<b>12.36</b>	21.04	43.67
130	<b>20.5</b>	6.22	9.36	<b>14.07</b>	23.35	49.78
135	<b>22.6</b>	6.61	10.66	<b>16.02</b>	27.53	56.42
140	<b>25.7</b>	7.25	11.67	<b>17.43</b>	29.44	61.50
145	<b>28.8</b>	7.85	12.86	<b>19.68</b>	32.74	70.42
150	<b>31.9</b>	8.58	14.38	<b>21.85</b>	38.15	78.46

**Table 11:** Observed and expected limits, for all tagging categories and all jet bins combined.



**Figure 15:** Expected and observed limits for this analysis.

## References

- [1] The CDF Collaboration, Search for the Standard Model Higgs Boson Production in Association with a W Boson using 5.7/fb. CDF Public Note 10239.
- [2] The CDF Collaboration, Measurement of the  $t\bar{t}$  Production Cross Section in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV using Lepton + Jets Events with Secondary Vertex  $b$ -tagging. CDF Public Note 7138.
- [3] Enrique Palencia, Measurement of the  $t\bar{t}$  Production Cross Section in  $p\bar{p}$  Collisions at  $\sqrt{s} = 1.96$  TeV Using Lepton+Jets Events in the CDF Detector at Fermilab. Ph.D. Thesis, CDF Public Note 8772.
- [4] M.L. Mangano, M. Moretti, F. Piccinini, R. Pittau, A.D. Polosa, ALPGEN, a generator for hard multiparton processes in hadronic collisions. [arXiv:hep-ph/0206293](https://arxiv.org/abs/hep-ph/0206293).
- [5] Torbjorn Sjostrand, Stephen Mrenna, Peter Skands, PYTHIA 6.4 Physics and Manual, [arXiv:hep-ph/0603175](https://arxiv.org/abs/hep-ph/0603175).
- [6] J. Alwall et.al., MadGraph/MadEvent v4: The New Web Generation, JHEP 0709 (2007).
- [7] Thomas Junk, Confidence Level Computation for Combining Searches with Small Statistics. [arXiv:hep-ex/9902006](https://arxiv.org/abs/hep-ex/9902006).
- [8] D. Acosta et al., Nucl. Instrum. Methods, A494, 57 (2002).